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ESTIMATING CHANNEL INFILTRATION FROM SURFACE RUNOFF IN THE SOLITARIO CANYON WATERSHED, YUCCA MOUNTAIN, NEVADA

Prepared for

Nuclear Regulatory Commission
Contract NRC-02-97-009

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December 1998

ABSTRACT

It has been hypothesized that the Solitario Canyon watershed, just west of Yucca Mountain, Nevada, could provide a zone of focused groundwater recharge through its ephemeral channels that might be an important factor in the performance of the potential repository for high-level radioactive waste. To examine this possibility, the KINEROS2 rainfall-runoff model (Smith et al., 1995) was used to estimate the infiltration from surface runoff in each of 79 channel elements using a 100-yr simulated rainfall sequence and two sets of saturated hydraulic conductivity (KS) values. The annual average estimated infiltration ranged from 0.18 to 0.57 mm/yr (expressed as depth over the entire 10.7 km^2 watershed). Evaporation and transpiration by vegetation near the channels were neglected so these quantities of channel infiltration are not assumed to be groundwater recharge. The simulated rainfall intensities compared favorably with depth-duration-frequency curves for nearby stations. The simulated 100-yr peak discharge rates for Solitario Canyon and for four subwatersheds exceeded the U.S. Geological Survey (USGS) 100-yr rates for the lowest values of KS and were below the USGS values for the higher values of KS, suggesting the true value of peak discharge (and channel infiltration from surface runoff) is bounded by those obtained for the two 100-yr simulations.

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ACKNOWLEDGMENTS

This work was prepared to document work performed by the Center for Nuclear Waste Regulatory Analyses (CNWRA) for the Nuclear Regulatory Commission (NRC) under Contract No. NRC-02-97-009. The report is an independent product of the CNWRA and does not necessarily reflect the views or regulatory position of the NRC.

This report was greatly improved by thorough technical, programmatic, and editorial reviews provided by Pierre Julien (Colorado State University), Randall Fedors (CNWRA), Patrick Mackin (CNWRA), and Barbara Long (CNWRA). Randall Fedors assisted in the development of figure 2-1. Finally the careful formatting and preparation of tables performed by Arturo Ramos is greatly appreciated.

Use of the KINEROS2 program is greatly appreciated along with discussions with staff from the Agricultural Research Service, U.S. Department of Agriculture: D.C. Goodrich, C. Unkrich, and R. Simanton of the Southwest Watershed Center, and R.E. Smith of Fort Collins.

QUALITY OF DATA, ANALYSES, AND CODE DEVELOPMENT

DATA: Measurements characterizing channel cross-sections, noted in section 2.2 of this report, have been recorded and described in scientific notebooks by the CNWRA authors following QAP-001; no other CNWRA-generated original data are contained in this report. Sources for other data should be consulted for determining the level of quality for those data.

PROGRAMS: KINEROS is a widely-used, documented, publically available program originally released in 1990. The U.S. Department of Agriculture continues to upgrade this program along with published documentation describing the modifications. The configuration of KINEROS2 will be submitted for control under the CNWRA Technical Operating Procedure (TOP)-018.

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1 INTRODUCTION

1.1 BACKGROUND

Yucca Mountain, (YM) Nevada, approximately 160 km northwest of Las Vegas, Nevada, is the potential site of a geologic repository for high-level radioactive waste. The repository would be located approximately 250 m above the water table and within the unsaturated zone (UZ), which is up to 750 m thick. The magnitude of deep percolation fluxes past the repository horizon has been identified as a critical factor in the potential repository performance, (e.g., Nuclear Regulatory Commission, 1992, 1995; Electric Power Research Institute, 1992, 1996). Sources of fluxes traversing the UZ include water that has percolated below the root zone on upland areas and water that has infiltrated in the beds of ephemeral channels within the repository footprint. Flint et al. (1996) present a summary of methods used to estimate the quantity of water percolating below the root zone on YM. Estimates of annual average percolation for areas similar to Solitario Canyon range from zero to 6.5 mm/yr. It is generally agreed that the greatest amounts of net recharge occur where shallow soils overlie fractured bedrock and that little or no deep percolation occurs in deep colluvium and alluvium.

The washes in the eastern portion of the Solitario Canyon watershed, just west of YM, are similar to the washes in the repository footprint, providing an independent check on U.S. Department of Energy simulations within the repository footprint. It has also been hypothesized that the Solitario Canyon watershed could provide a zone of focused recharge through its ephemeral channels. The Solitario Canyon watershed is at a higher elevation than the proposed repository, up-dip from the repository and at a lower elevation than a layer that is expected to provide significant damping of vertical percolation pulses. The purpose of this investigation is to estimate the average annual infiltration into the ephemeral channels of Solitario Canyon attributed from to surface runoff under current climate conditions.

The best way to estimate the quantity of water infiltrating into ephemeral channels during runoff is to measure inflows and outflows of individual channel reaches. Neutron probe observations can also be used to track transient inputs of water within the channel bottom. Both of these methods are relatively expensive and would require measurements over a long period of time to obtain accurate estimates of mean annual infiltration (MAI) at a limited number of locations. They also could not be used to estimate channel infiltration for future climate scenarios. The only feasible technique for estimating channel infiltration in all reaches and for future climates is to use a distributed rainfall-runoff model capable of estimating surface runoff from upland areas and the subsequent infiltration into channel beds. This study was intended to provide input to a two-dimensional porous media model that would include precipitation on the channel for all precipitation events, evaporation from the channel surface, and transpiration by streamside vegetation. Consequently, only infiltration attributed from surface runoff in the channels is considered herein and the resulting estimates of channel infiltration are not estimates of deep percolation.

1.2 CLIMATE

The climate of the Solitario Canyon watershed is affected by the interaction of weather systems with major topographical features. During the winter months, most of the weather systems providing moisture originate in the Pacific ocean and precipitation is deposited in the Sierra Nevada Mountains, resulting in a rain shadow encompassing the watershed. Moisture during the summer comes from the south and southeast borne by southerly winds that curve to the east in the watershed area. French (1983) defines three zones in southern Nevada: a deficit zone within the rain shadow, an excess zone southeast of the rain shadow, and a transition zone between them. Solitario Canyon is within the transition zone. The average annual precipitation is estimated to be 165 mm. There is significant seasonal variation, with a summer rainfall period having a maximum in August and a winter rainfall period including the months of October through April. The summer rainfall often occurs as thunderstorms with high intensities, while the winter rainfall generally has longer durations and lower intensities. The potential evapotranspiration (PET) in the vicinity of the watershed is much greater than the precipitation. The calculated PET at the nearby city of Beatty, Nevada, ranged between 130 and 210 cm for years between 1961 and 1976 (Nichols, 1987). A map developed by Shevenell (1996) shows PET for YM in the range of 120–180 cm/yr.

1.3 DESCRIPTION OF WATERSHED

The Solitario Canyon watershed has an area of 10.7 km^2 and ranges in elevation from 1,180 to 1,700 m. The main channel is fault controlled and the west flank of YM forms the contributing area from the east. The channels entering from the east are steep and show little branching. On the west side of the main channel, slopes are more gentle and contributing channels exhibit a dendritic pattern. Soils have been described as gravelly to very gravelly sandy loams with loamy skeletal inclusions[1] and are shallow on ridgetops and steep slopes. It has been estimated that 48 percent of the soils on YM have depths of 50 cm or less (Flint et al., 1996). Vegetation is sparse and typical of the northern boundary of the Mojave Desert and the transition zone to the Great Basin.

1.4 KINEROS2 MODEL

The KINEROS2 model is an improved version of KINEROS (Woolhiser et al., 1990) described in detail by Smith et al. (1995). It is a distributed model, with topographic features and the channel network represented as cascades of planes contributing flow to channels either as concentrated flow at the upper boundary or as uniformly distributed lateral flow. Rainfall rates may be specified independently for each element by interpolation between rain gages. The Smith-Parlange (1978) equation is used to describe interactive infiltration at each computational node on both plane and channel elements. Two soil layers can be specified for the plane and channel elements. Overland and channel flows are described by one-dimensional kinematic wave equations solved by finite difference techniques. The KINEROS model, an earlier version of KINEROS2, has been thoroughly tested over a range of catchment sizes in a semiarid environment (Goodrich, 1990).

[1]U.S. Department of Agriculture, Soil Conservation Service. 1986. Advance Copy of Pedologic Map and Report Including Part of Yucca Mountain. USDA, SCS, P.O. Box 4850, Reno, NV. (cited by Schmidt, 1988).

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2 WATERSHED GEOMETRY AND MODEL PARAMETERS

2.1 PLANE ELEMENTS

The 10.7 km^2 watershed was subdivided on a 20-m contour interval map using techniques suggested by Woolhiser et al. (1990). This subdivision resulted in 204 plane elements (mean length = 223 m, mean slope = 0.25). The subdivision of the watershed into planes and channels is shown in figure 2-1. Some of the slopes in the Solitario Canyon watershed (defined as tangent of the slope angle) are steep—as much as 0.57. Several of the steep slopes are represented as plane elements cascading onto lower plane elements with flatter slopes. This arrangement results in the formation of kinematic shocks (Kibler and Woolhiser, 1972). Because there is no explicit shock following scheme in KINEROS2, these shocks may lead to small volume balance errors for some elements. These errors, however, are always less than one percent and are not significant for the overall water balance.

2.2 CHANNEL ELEMENTS

The subdivision procedure resulted in 79 channel reaches with an average length of 381 m. The average channel slope was 0.11, ranging from 0.30 in the headwaters to 0.03 for the lowest channel reach. The map did not provide sufficient detail to estimate the channel cross section properties. In KINEROS2, simple channel cross sections are represented by a trapezoid with bottom width, *BW*, and side slopes, SS1 and SS2. These parameters were estimated for 10 channel elements based on cross sections obtained by field survey. Four channels (244, 248, 267, and 274) could not be represented as simple trapezoids, so were modeled as compound channels with additional parameters describing the overbank section: width, slope, elevation difference between the main channel bottom and the overbank, and side slope. The channel properties of all other channel elements were estimated by relating the channel top width at 1-m depth to the contributing area using 13 measurements. This relationship is shown in figure 2-2. The average side slopes of the measured sections were 0.26 and 0.27. By projecting these slopes to zero depth, the bottom width can be estimated. The intercept was adjusted so that the bottom width will be zero when the contributing area is zero, leading to the equation:

$$BW = 4.14A \tag{2-1}$$

where *BW* is in meters and *A* is the contributing area in km^2. The two data points showing a large width at a small area are for channel sections of small tributaries near the junction with the main channel of Solitario Canyon. There was considerable deposition of sediment so these sections are not representative and were not included in the regression relationship. Channels in the watershed may switch between braided and incised and back within a reach modeled as a single prismatic channel. The approximations were verified in the field by measuring the width of the active channel at 11 additional sites. The measurements compare well with the regression relationship (figure 2-2) except for three measurements where the channel is constricted by deposition from tributary channels. The bottom widths for these channels were set at measured values.

The wetted areas of the channels and overbank sections (if any) are important factors defining channel infiltration during a runoff event (Freyburg, 1983; El-Shinnawy, 1993). In studies at the Walnut Gulch experimental watershed, it was found that the trapezoidal channel approximation provided reasonable

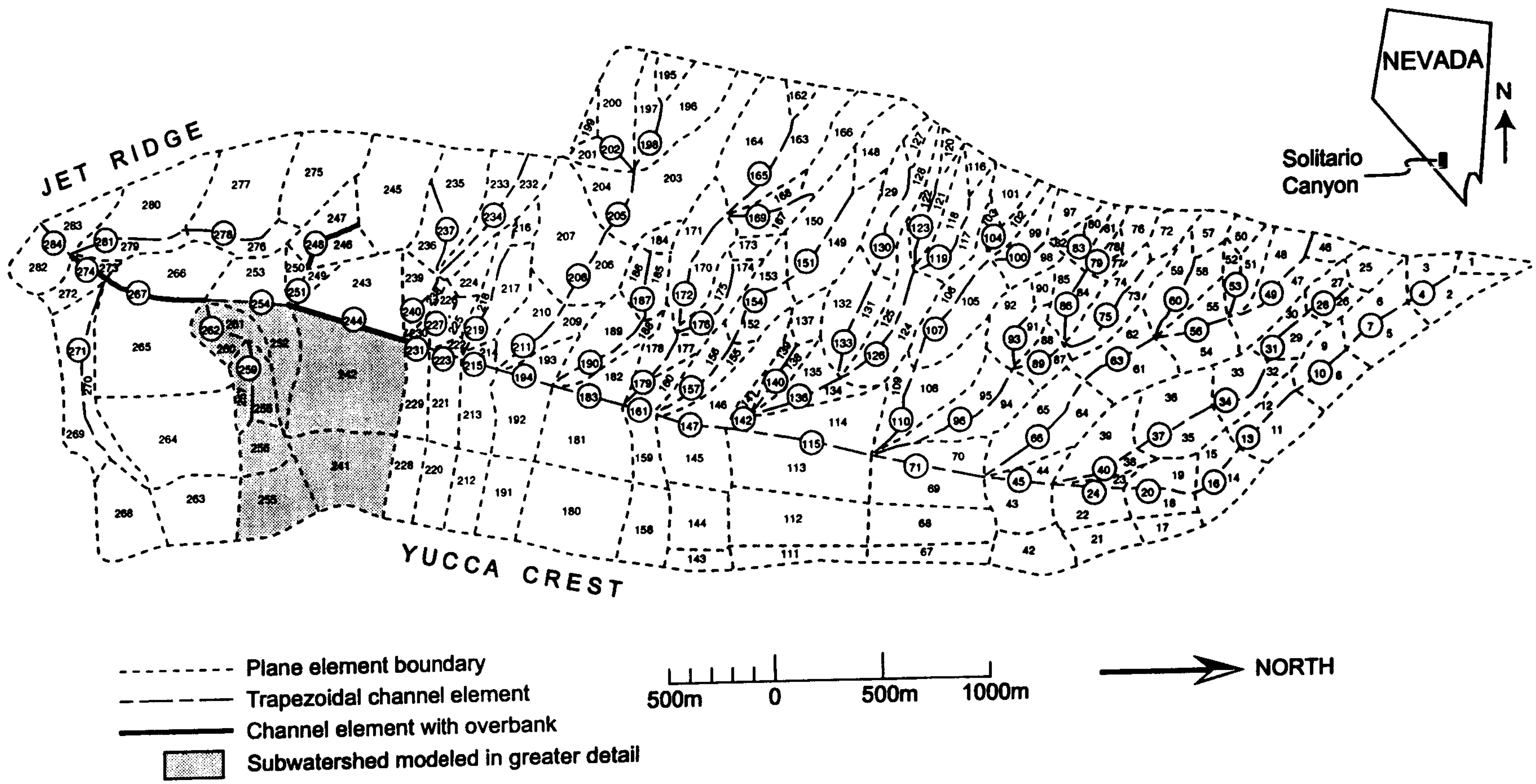

Figure 2-1. Map of Solitario Canyon watershed showing subdivision into plane and channel elements

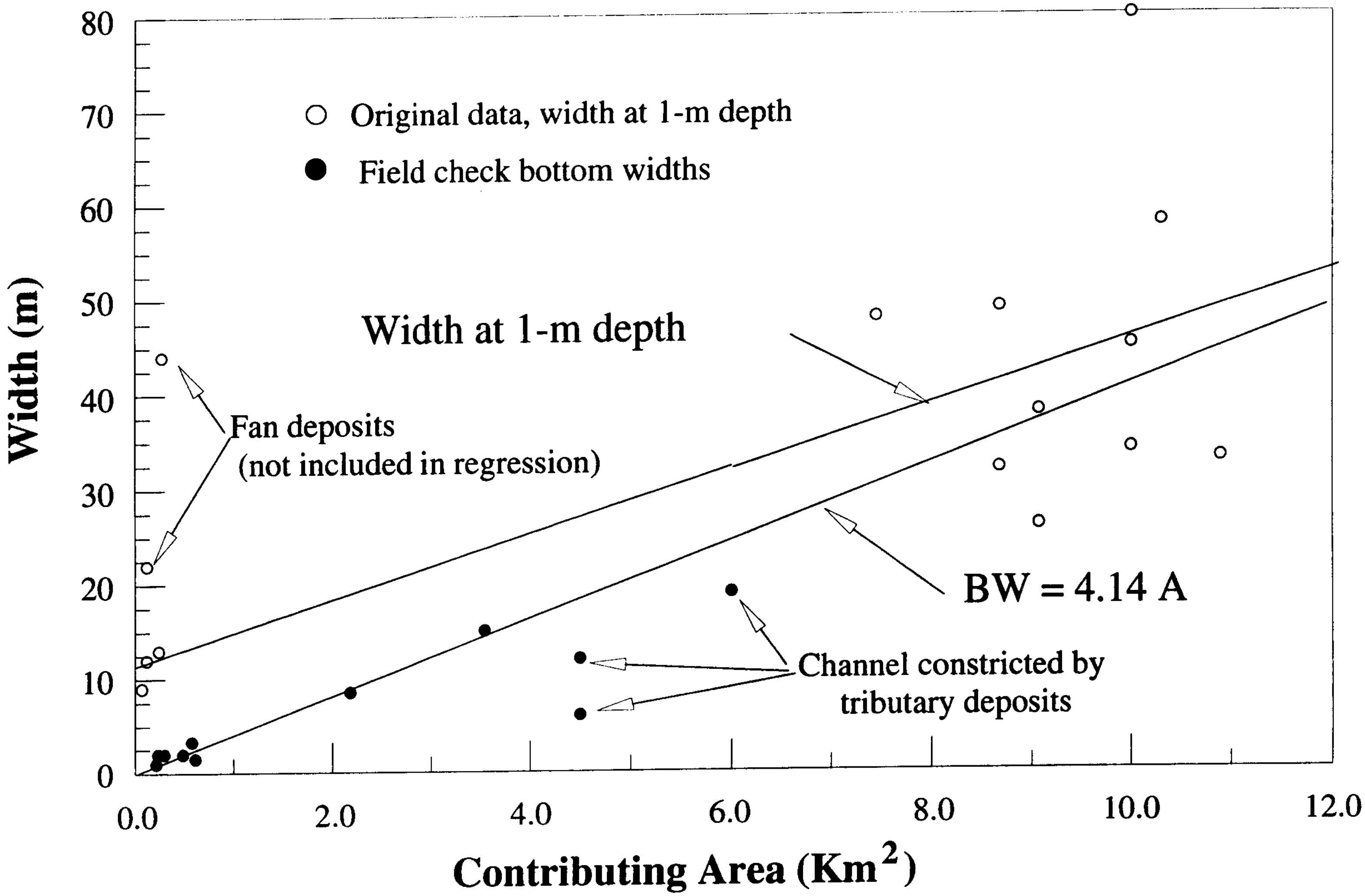

Figure 2-2. Relationship between channel bottom width and contributing watershed area

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results from the hydraulic standpoint but led to overestimates of channel infiltration because the width was too great at low flows (Unkrich and Osborn, 1987). The following empirical expression was modified from Smith et al. (1995) to reduce the effective infiltrating channel width as a function of the water depth:

$$P_e = \mathbf{Max}\left[\mathbf{Min}\left\{\frac{h}{0.0856\sqrt{BW}},\ 1\right\}P_w\ \ 0.05BW\right] \tag{2-2}$$

where P_e is the effective wetted perimeter for infiltration, h is the local depth, and P_W is the wetted perimeter of the trapezoidal section. All units are in meters. Thus, at the smallest depths, the minimum effective wetted perimeter is 5 percent of the bottom width and when $h > 0.0856(BW)^{1/2}$, $P_e = P_W$. The effective wetted perimeter calculated by Eq. (2-2) was acceptably close to the wetted perimeter for the measured channel cross sections. Freyburg (1983) found that the direct effects of water pressure on the channel bed are overshadowed by the effects of variations in the wetted perimeter so the pressure head attributed to ponded water is not considered for the Smith-Parlange channel infiltration routine.

2.3 COMPUTATIONAL INCREMENTS

The KINEROS parameter, CLEN, that controls the size of the Δx increments in the finite difference solution of the kinematic wave equation for both planes and channels, was set at 300 m, which is between the mean length of overland flow and the mean channel length, and results in an average Δx of approximately 20 m. The computational time increment was set at one minute. Smaller time steps occur whenever the rainfall rate changes.

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3 PARAMETERS AND INITIAL CONDITIONS FOR PLANE ELEMENTS

3.1 SATURATED HYDRAULIC CONDUCTIVITY

The saturated hydraulic conductivity (KS) under imbibition, is perhaps the most important model parameter and one that is difficult to estimate for field conditions (Goodrich, 1990). It is known to exhibit a high degree of spatial variability due to changes in soil type, degree of erosion, rock content, and vegetative cover. KS can be estimated using several types of data, each with different degrees of uncertainty: (i) soil textural characteristics, (ii) infiltrometer measurements, (iii) rainfall simulator experiments, and (iv) rainfall and runoff measurements. No sufficiently detailed rainfall and runoff measurements, infiltration measurements, or rainfall simulator experiments have been made in the Solitario Canyon watershed. Schmidt (1988) made detailed measurements of soil texture in part of the watershed and used a regression equation to estimate the KS. His estimates ranged from 19.3 to 21.1 mm/hr and he found no significant difference due to position on the slope. The regression equation is based on the clay and silt mass fractions of the fine soil components (<2mm) and does not account for rocks in the soil profile. The rather uniform nature of the fine components of the soil is consistent with an aeolian source. The soils have an average volumetric rock content of 37.7 percent (Schmidt, 1988) so the effective hydraulic conductivity would be smaller (12.02–13.1 mm/hr) using a correction factor of $(1-V_r)$, where V_r is the volumetric rock content.

Simanton et al. (1986) reported on rainfall simulator experiments carried out in the Nevada Test Site (NTS). The experiments were designed to provide information on erosion rates and consisted of simulations in each spring and fall of 1983 and 1984 on six plots at Area 11 and six plots near Mercury, Nevada. A summary of the data collected was published by Lane (1986, Appendix A). Detailed rainfall and runoff data for the simulator plots were obtained from Roger Simanton of U.S. Department of Agriculture, Agriculture Research Service, Tucson, Arizona. A comparison of the soil textures at Area 11, Mercury, and YM (Schmidt, 1988) is shown in table 3-1.

The YM soils have a higher silt and clay content suggesting they may have a lower KS. The textural characteristics of soils at Mercury, rather than Area 11, are closer to those at YM, so the data from the two natural plots at Mercury were analyzed using the KINEROS2 model to obtain estimates of both KS and the net capillary drive (G).

Each of the spring and fall simulations consisted of three runs: (i) a dry run of 60 min with dry initial condition; (ii) a wet run of 30 min 24 hr after the dry run; and (iii) a very wet run of 30 min about 30 min after the wet run (Simanton et al., 1986). An initial value of KS was estimated from the very wet run by dividing the difference between the rainfall volume and the runoff volume by the duration of the rainfall. The initial value of parameter G was estimated from soil textural information. These estimates were then used as starting values in an iterative procedure to match the volumes of runoff (within 1 mm) and the principal features of the runoff hydrographs for the dry run and the combined wet and very wet runs. The initial saturation condition (SAT) for the dry run was assumed equal to the average for that month measured at nearby Rock Valley (Lane et al., 1984). The estimated values of KS for both plots are shown in table 3-2. Figure 3-1 shows observed and computed hydrographs for the wet runs for Plot 11 for spring 1983. Similar degrees of fit were obtained for all runs.

Table 3-1. Soil textural comparison

(<2 mm fraction)*				
Location	**Coarse sand (%)**	**Fine sand (%)**	**Silt (%)**	**Clay (%)**
Area 11	15.2	69.6	14.5	0.7
Mercury	20.4	58.8	14.8	6.0
Yucca Mountain	—	60.8**	26.1	13.2

*Data from Area 11 and Mercury from Romney et al. (1986), Yucca Mountain from Schmidt (1988)
**No distinction made between coarse sand and fine sand

Table 3-2. Estimated values of saturated hydraulic conductivity, Mercury, Nevada, rainfall simulator plots

Run	Initial Condition	KS Plot 7 mm/hr	KS Plot 11 mm/hr	Average KS mm/hr
Spring 1983	Dry Wet	23. 18.	30. 17.	26.5 17.5
Fall 1983	Dry Wet	9.5 9.5	12. 7.5	10.75 8.5
Spring 1984	Dry Wet	24. 24.	30. 24.	27. 24.
Fall 1984	Dry Wet	13. 13.	18. 23.	15.5 18.
Spring Average	—	22.25	25.25	23.75
Fall Average	—	11.25	15.12	13.18
Annual Average	—	16.75	20.19	18.47

Considering variability of soil properties, the results for the two plots are quite consistent; however, there appear to be real seasonal differences in the KSs, with consistently higher values in the spring. This type of seasonal variability also has been observed at the Walnut Gulch Experimental watershed in Arizona (Simanton and Renard, 1986). A possible explanation is that freezing and thawing during the winter loosens the surface soil and summer rains compact it again leading to lower conductivities in the fall.

Plot 7 has lower values of saturated hydraulic conductivity than Plot 11. Therefore, Solitario Canyon simulations using the seasonal or average values for Plot 7 will result in higher runoff and channel infiltration estimates than would simulations using average values of saturated conductivity for the two

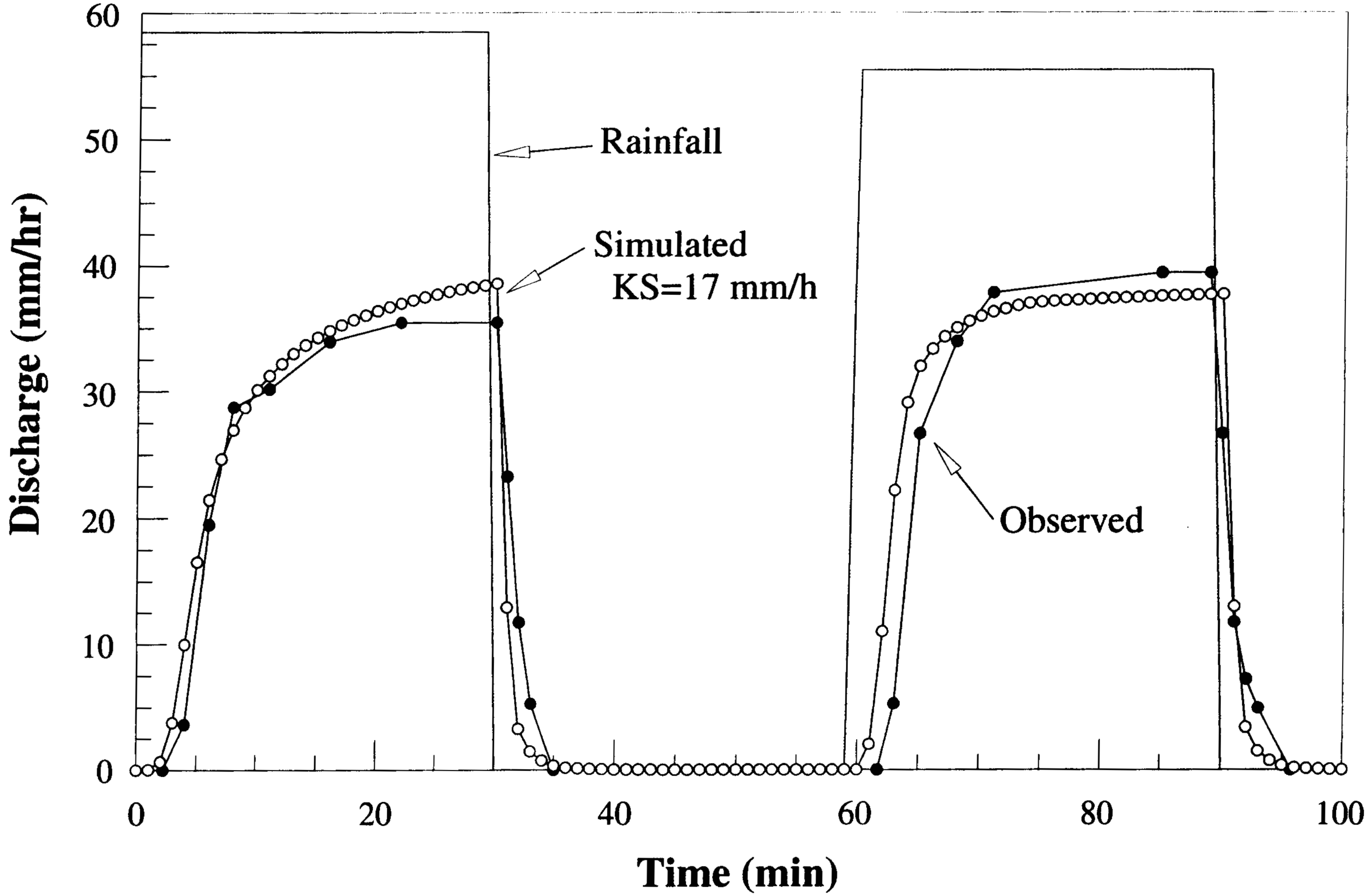

Figure 3-1. Observed and computed hydrographs for the wet and very wet runs for Mercury, Nevada, Plot 11 for spring 1983

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plots. Also, the global average of 18.47 mm/hr is less than the value uncorrected for rock content determined by Schmidt (1988). Although there is some between-plot variation, it appears the seasonal variation is larger.

3.2 NET CAPILLARY DRIVE

Based on soil texture alone, G was estimated to be 128 mm. A value of 50 mm resulted in a better fit to the rising hydrographs and the more consistent estimates of KS for the rainfall simulator data. This value is within one standard deviation of the geometric mean for a sandy loam soil (table 3-2 of Woolhiser et al., 1990). It should be noted that a high rock content may reduce the effective value of G.

3.3 COEFFICIENT OF VARIATION OF SATURATED HYDRAULIC CONDUCTIVITY

The program KINEROS2 represents the saturated hydraulic conductivity as a lognormally distributed random variable described by the mean, KS, and the coefficient of variation (CV) (Smith et al., 1990). A CV value of 0.4 gave the best results for the rainfall simulator plots. It is expected that CV should increase as does the size of plane elements, so CV was set to 0.8 for plane elements for Solitario Canyon, a value obtained by Goodrich (1990) for a semiarid watershed.

3.4 POROSITY

Lane et al. (1984) reported an average porosity of 0.34 for samples from 13 locations and 72 profiles in Rock Valley, within the NTS; this value was used for the porosity (POR) for all simulations. Schmidt (1988) did not provide specific data on soil porosity; however, using his values of volumetric rock content, rock particle density, and total bulk density, and assuming the particles <2mm have a density of 2.65, the calculated porosity is 0.388–reasonably consistent with measured values.

3.5 ROCK FRACTION

Because both KS and G were obtained from rainfall simulator data, the rock fraction (ROC) has been set equal to zero for every plane element (Woolhiser et al., 1990). Had KS and G been estimated for the fine portion of the soil, POR would have been adjusted automatically for the ROC.

3.6 MICROTOPOGRAPHIC PARAMETERS

In KINEROS2, lateral microtopographic variations are represented as parallel triangular sections with relief (RE) the depth in mm and spacing (SPA) the average spacing of the crests (or bottoms) in meters. Runoff volumes are most sensitive to RE, which, conceptually, should increase downslope to reflect greater rill incision and concentration. No data are available from Solitario Canyon to provide an estimate of what RE should be and how it should vary in a cascade of planes. In the absence of definitive data, RE was set at 50 mm for all single planes, 100 mm for the second plane in a cascade, and 150 mm for the third plane. In an empirical study of runoff from the Walnut Gulch Experimental watershed, Simanton et al. (1973) presented a relation between the Soil Conservation Service (SCS) curve number and the watershed area:

$$CN = 90.227A^{-0.0088} \tag{3-1}$$

where CN is the curve number and A is the watershed area in hectares. When this expression is used to calculate a curve number and the SCS curve number method is used to calculate runoff per unit area as a function of area for a rain of 25.4 mm the decrease in runoff per unit area is similar to that observed for the cascades of planes with the parameters as set previously. SPA was set at 1 m.

3.7 INITIAL RELATIVE SOIL SATURATION

Parameter files were established to account for seasonal variation of SAT as well as KS. Values for SAT were based on the monthly averages measured over a 5-year period at nearby Rock Valley (Lane et al., 1984). As a guide, SAT is estimated as 0.25 for permanent wilting and 0.58 for field capacity (Woolhiser et al., 1990)

3.8 MANNING'S n—OVERLAND FLOW

A Manning's n of 0.151 was selected from the information provided in tables 6-2 and 6-3 in Woolhiser et al. (1990), pictures taken at Solitario Canyon, and from data presented by Weltz et al. (1992) for brush lands in the Mojave Desert.

4 PARAMETERS AND INITIAL CONDITIONS FOR CHANNEL ELEMENTS

KS for channels was initially set at 61 mm/hr based on textural estimates and table 2 in Woolhiser et al. (1990). Observations during a field trip revealed differences between the channel bed materials in the upper reaches and the lower reaches of the main channel. Specifically, in the lower reaches, the surface was covered with a thin layer of gravel underlain by fine sand. In the upper channel reaches, the sand was not generally observed. Logically, the saturated hydraulic conductivity of the bed materials in the upper channel reaches should be higher. Accordingly, KS was increased to 91 mm/hr for upper channels, based on a range suggested by Flint et al. (1996). Britch (1990) sampled channel materials in the Pagany Wash watershed on the east side of YM and calculated KSs of 130 mm/hr. It is not clear if he reduced the conductivities for rock content of the channel alluvium. The channel bed was assumed to consist of a single, deep layer so there would be no effect of an underlying layer with lower hydraulic conductivity. This assumption is probably valid for the major channels. The alluvium in small, steep channels is underlain by fractured bedrock so the single layer assumption may lead to an overestimate of infiltration.

G was set at 63 mm based on textural estimates and table 2 of Woolhiser et al (1990). POR was set at 0.44 corresponding to the texture of loamy sand in table 2 of Woolhiser et al. (1990). ROC was set to zero because channel KS was estimated based on the overall textural characteristics. SAT was set at 0.13 corresponding to permanent wilting for loamy sand. A Manning's n of 0.0651 was chosen for the first and second order channels and n = 0.0511 was chosen for the third order channels based on pictures taken of the channels at Solitario Canyon and information in table 6.1 in Simons, Li and Associates (1982) for natural channels with some weeds and brush with irregular sections. (Note: The use of three significant figures for Manning's n and other parameters or variables does not imply that degree of accuracy.)

5 PRECIPITATION

5.1 BACKGROUND

The KINEROS model requires high-time-resolution rainfall data for input. For example, Woolhiser (1986) recommends a minimum resolution of 5 min. Although there are some raingages within and near the Solitario Canyon watershed, the records are short and data from raingages in the vicinity with a longer period of record do not have the required time resolution. An alternate approach is to perform a two-stage disaggregation: (i) from historical or simulated daily rainfall to showers, defined by a depth and a duration and (ii) from showers into short time period intensities using techniques described by Hershenhorn and Woolhiser (1987) and Woolhiser and Osborn (1985). This two-stage approach was used in this study.

5.2 DAILY PRECIPITATION MODEL

The program USCLIMAT.BAS (Hanson et al., 1994) was used to simulate daily rainfall having an appropriate seasonal distribution and annual mean precipitation for Solitario Canyon. The daily precipitation model is called the Markov chain—mixed exponential model (Roldán and Woolhiser, 1982; Woolhiser and Roldán, 1982). The occurrence of daily precipitation is described by a first-order Markov chain and the distribution of rainfall depth, on a wet day, is described by a mixed exponential distribution. The seasonal variation of model parameters is described by Fourier series with amplitudes and phase angles estimated by maximum likelihood techniques using 20–40 yr of high-quality daily rainfall data. The program USCLIMAT.BAS includes parameter files for several stations in Nevada, but the nearest stations that have average annual rainfall that brackets the estimated annual precipitation at YM (165 mm) are Las Vegas, Nevada, and St. George, Utah. Mean annual precipitation at Las Vegas is 108 mm with a mean annual number of wet days 26.5. Mean annual precipitation at St. George is 215 mm with 46.26 wet days. The means, amplitudes and phase angles for these two stations were averaged and the mean of the weighting parameter, α, and the annual mean of the probability of a wet to dry transition were adjusted to obtain the desired annual precipitation. The theoretical mean number of wet days for the Solitario Canyon daily precipitation model is 37, while the average number of wet days calculated by the regression equation given by French (1983) ranges from 37 at 1,300 m elevation to 41 at 1,500 m. This regression is based on data from many Nevada stations and the theoretical mean of 37 is well within the scatter of the data.

Three 50-yr simulated records of daily precipitation were generated and monthly averages and standard deviations calculated. The monthly averages usually fall between the values for St. George, Utah and Las Vegas, Nevada.

5.3 DISAGGREGATION OF DAILY RAINFALL

The technique for disaggregating daily rainfall into showers proposed by Hershenhorn and Woolhiser (1987) requires a joint distribution between the daily amount of rainfall and the discrete number of showers in the day. These showers may be complete in that they start and end within the day, or they may be partial showers that continue over midnight. Given the number of showers, the total rainfall depth is fragmented into individual shower depths and each shower is assigned a duration based on a joint distribution between duration and shower depth. Finally, each shower is assigned a starting time within the day. The Hershenhorn and Woolhiser (1987) joint distribution between the daily depth of rainfall and the discrete number of showers was developed for rainfall in southern Arizona and is probably reasonable for summer thunderstorm rainfall conditions. In an arid region such as this, the most frequent number of showers in a day is one, so the results are probably not greatly affected by this assumption. In this study it was assumed all showers began and ended during the day (i. e., no rainfall continued over midnight).

The durations of all showers over 12.7 mm were simulated by Monte Carlo techniques using the relationship

$$\boldsymbol{D} = \exp\left(\boldsymbol{a} + \boldsymbol{b} \ln \boldsymbol{P} + \epsilon \boldsymbol{S}\right) \tag{5-1}$$

where D is the duration in minutes, P is the shower depth (in mm), a and b are parameters, S is the standard error of estimate in the linear relationship between ln D and ln P, and ϵ is a standard normal deviate. The parameters a, b, and S (3.415, 0.3785, and 1.8885 respectively) were obtained from an analysis of summer thunderstorm rainfall in Arizona (Hershenhorn and Woolhiser, 1987). These parameters may be good estimates for summer thunderstorm rainfall at YM but would not be appropriate for winter storms as they would tend to underestimate the shower duration. Because winter storms in this region are generally from Pacific fronts and have much longer durations than summer storms, the relationship between shower depth and duration during the winter season, October through April, was changed by multiplying the duration obtained from Eq. (5-1) by 4.21, which is the ratio of average durations of winter and summer storms at Walnut Gulch, Arizona (Woolhiser and Osborn, 1986; Woolhiser and Econopouly, 1986). The maximum duration allowed for winter storms was 480 min.

5.4 DISAGGREGATION OF RAINFALL EVENTS

Techniques described by Woolhiser and Osborn (1985) and Woolhiser and Econopouly (1986) were used to disaggregate each shower into 20 depth increments for equal time increments of $0.05D$, where D is the shower duration in minutes.

5.5 SIMULATED RAINFALL STATISTICS

Three 50-yr sequences of precipitation were simulated. In the first 50-yr rainfall simulation, the same relationship was used between shower duration and depth for both the summer and winter seasons. The simulated maximum intensities for various durations and frequencies were higher than those calculated by French (1983) for the McCarran Airport at Las Vegas, Nevada.

The second and third 50-yr simulated rainfall sequences were combined to form a 100-yr simulated record. The disaggregation procedure resulted in 208 showers greater than 12.7 mm. Maximum intensities for time intervals of 5, 10, 15, 20, 30, 60, and 120 min for each of the simulated storms were calculated. These intensities were ordered and plotting positions calculated for the 100 largest storms (a partial duration series). The intensities are plotted versus return periods, T, for 10- and 60-min durations in figure 5-1a,b. Intensities were calculated from the relationship presented by French (1983) are:

$$\boldsymbol{I}(\boldsymbol{T}) = \phi\left(\boldsymbol{T}\right) \boldsymbol{D}^{-\Gamma(\boldsymbol{T})} \tag{5-2}$$

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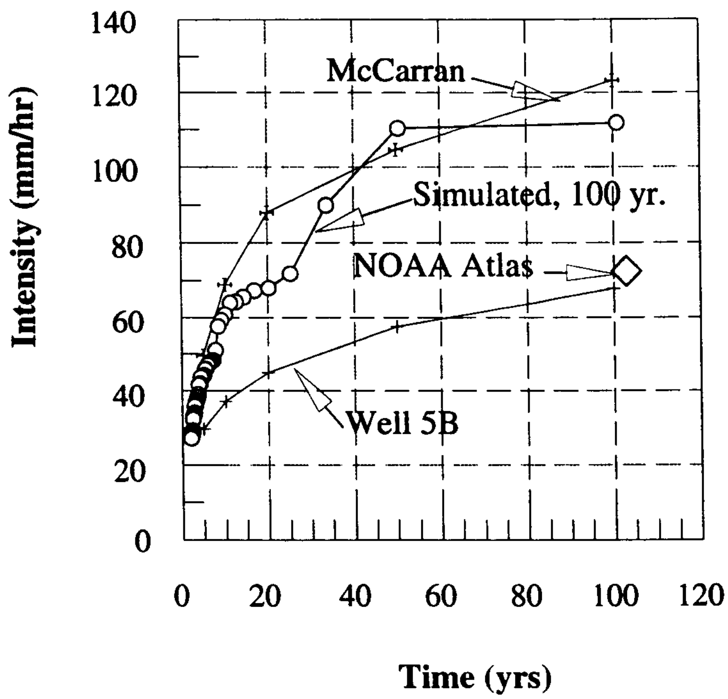
a.



b.

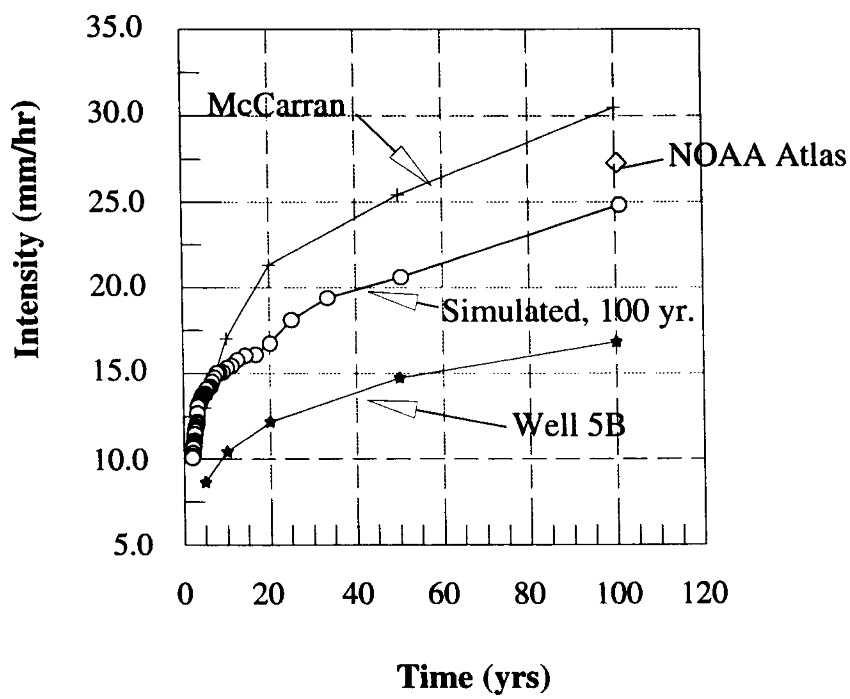


Figure 5-1. Intensity-duration-frequency relations for simulated rainfall compared with data from McCarran International Airport and Nevada Test Site Well 5B analyzed by French (1983) and National Oceanographic and Atmospheric Administration Atlas 100-yr intensities. (a) 10 min duration and (b) 60-min duration

where $I(T)$ is the intensity for a return period of T years, D the duration in minutes, and $\Phi(T)$ and $\Gamma(T)$ parameters that vary with T. Also shown are the 100-yr frequencies obtained from the NOAA Atlas (Miller et al., 1973). The parameter values used to calculate the points shown in figure 5-1a,b were obtained by French (1983) from an analysis of the records at the McCarran International Airport at Las Vegas, Nevada and Well 5B at the NTS. An examination of figure 5-1a,b reveals that the curves for simulated storms for all durations compare favorably with those from the records for nearby stations. The simulated intensities are much closer to the curves for McCarran Airport than they are to those for Well 5B. It should be noted that French (1983) had only 16 yr of rainfall data for Well 5B (compared to 49 yr at the McCarran Airport) so the Well 5B curves are not reliable. The 100-yr intensities from the NOAA Atlas are closer to those for Well 5B for the short durations, but approach the values for McCarran Airport for the longer durations. Tung (1987) performed a first order, second moment analysis of the uncertainty in the maps in the NOAA Atlas. Using Chicago, Illinois, as an example, he calculated standard deviations of the published intensities for several durations and recurrence intervals. The coefficients of variation of the intensities for the 100-yr frequency range from 0.26 for a 5-minute duration to 0.29 for 60 min. Given this level of uncertainty (and the coefficients of variability would probably be greater in an arid area) it appears that the simulated intensities are reasonable.

5.6 SPATIAL VARIABILITY OF RAINFALL

It is well known that thunderstorm rainfall in the southwest exhibits extreme spatial variability. There is no accepted model for simulating spatially varied rainfall for short time intervals. In this study we assume that the simulated rainfall is uniform over the watershed. Osborn et al. (1993) calibrated the KINEROS model using runoff data from a 6.3 km^2 subwatershed of the Walnut Gulch watershed and rainfall data from 10 recording raingages. When they simulated the same runoff events but used rainfall data from a single, centrally located gage, they found that runoff volumes of 6 of the 10 calibration events and all of the medium to large events were overestimated (from 14 to 93 percent). It is likely that the simulated runoff volumes reported in this study will also be overestimates.

6 SIMULATION OF RUNOFF AND CHANNEL INFILTRATION

6.1 AVERAGE PLANE ELEMENT—SOLITARIO CANYON

The 208 simulated storms were first used as input to an overland flow plane with the geometric characteristics of an average plane element in the Solitario Canyon watershed model. Two sets of runs were completed. For the first set, both the SAT and the KS of the plane element varied seasonally and approximated the values of KS for Mercury, Nevada, Plot 7 in table 3-2, and the relative water content at 15-cm depth at Rock Valley shown in table 6-1. For the second set, the SAT was the same, but the KS was set at a constant value equal to the midrange of the values estimated by Schmidt (1988). These values are shown for both sets in table 6-2. Runs were made for two 50-yr sequences and the results combined for a 100-yr simulation. The objectives of this exercise were to determine which storms would cause significant runoff for Solitario Canyon and to obtain an estimate of the average annual runoff on an average upland area.

A negligible (zero or <0.1 mm) amount of runoff was generated by 131 of the storms for Set 1 and by 164 storms for Set 2, so these storms were not used as input to the Solitario Canyon watershed simulation. Runoff statistics for the average plane element are shown in table 6-3.

6.2 SOLITARIO CANYON WATERSHED—RUNOFF VOLUMES AND CHANNEL INFILTRATION

Computer runs were made for the entire Solitario Canyon watershed for the largest storms and for a few small storms. A power-function regression ($R^2 > 0.99$) was found to fit the relation between the total Solitario Canyon channel infiltration and the average plane runoff for each event. This relation is shown in figure 6-1.

The regression relations shown in figure 6-1 were used to estimate channel infiltration for all of the nonzero runoff events for the average plane. Using this technique, the estimated average annual channel infiltration for the first set of runs is 0.57 mm/yr and for the second set is 0.18 mm/yr expressed as depth over the entire watershed (see table 6-3). The area of the channels in the model is 1.5 percent of the watershed area. Therefore, the mean annual infiltrated depth per unit channel area ranges from 12 to 38 mm/yr. Because no runoff volume records are available for Solitario Canyon or for nearby watersheds of comparable size, it is difficult to judge the reliability of runoff and infiltration estimates.

The reasonableness of the runoff estimates was evaluated by using the peak runoff estimates for watersheds in the vicinity obtained from measurements of annual maximum stages (U.S. Department of Energy, 1988, table 3.2). These measurements were collected over a 15-yr period, so they would have a recurrence interval of about 15–16 yr. Since the rainfall simulation covered a period of 100 yr, the largest runoff event would have a calculated recurrence interval of 101 yr and the sixth largest would have a recurrence interval of 16.8 yr. The simulated rainfall event PAUG4 had the greatest simulated volume of runoff and the greatest peak rate of runoff from Solitario Canyon. The simulated rainfall event 1NOV10A led to the sixth largest volumes and peaks at the mouth of Solitario Canyon.

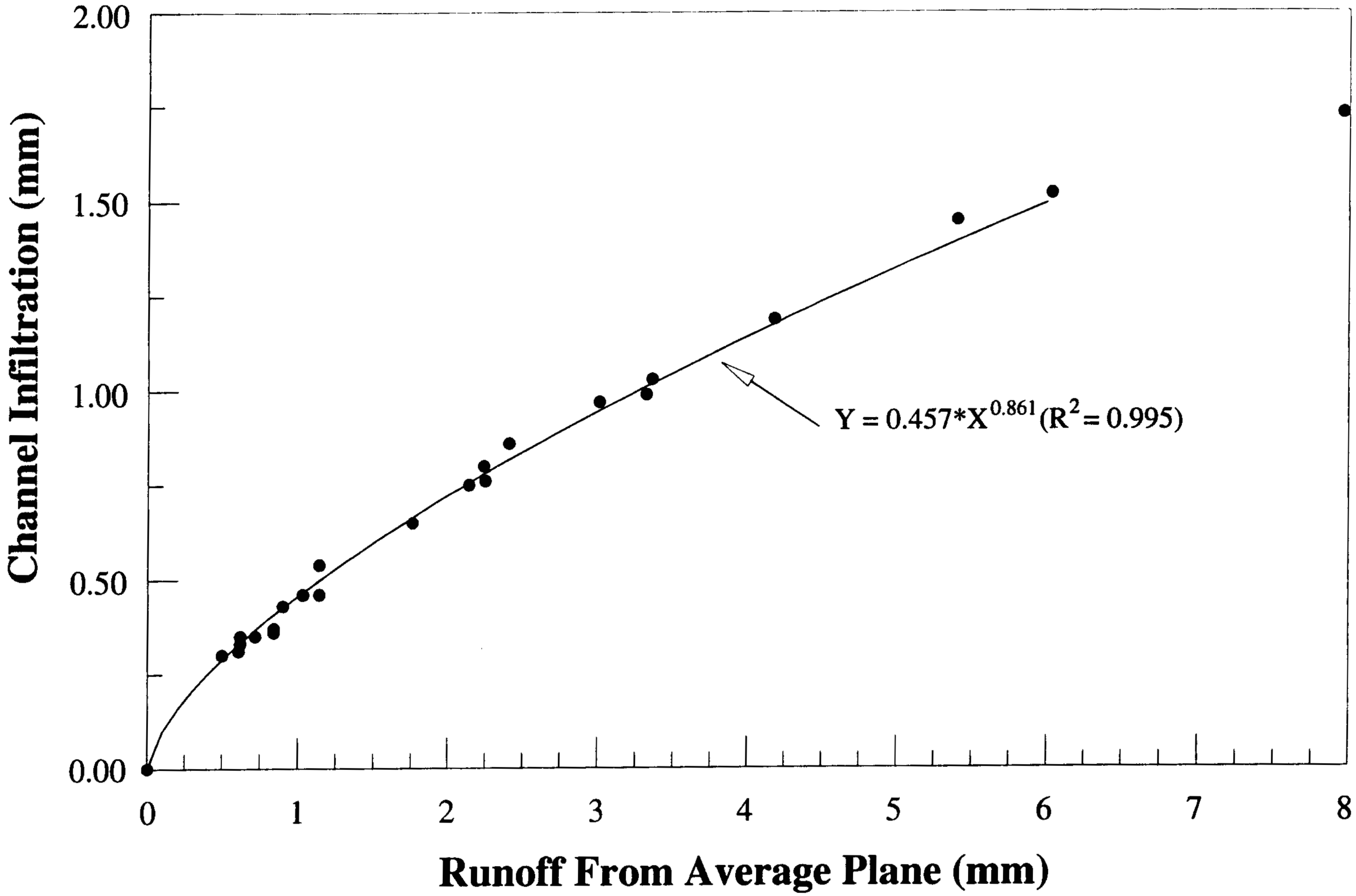


Figure 6-1. Total channel infiltration on the Solitario Canyon watershed as a function of runoff from an average plane for individual storms

Table 6-1. Average monthly water content at 15-cm depth

(Relative saturation based on a porosity of 0.34)		
Month	**Water Content (% by volume)**	**Relative Saturation**
January	11.4	0.33
February	12.6	0.33
March	12.6	0.37
April	9.4	0.27
May	6.3	0.18
June	4.7	0.14
July	4.9	0.14
August	5.6	0.16
September	5.6	0.16
October	5.1	0.15
November	7.4	0.22
December	8.6	0.25
Annual	7.8	0.23

Table 6-2. Seasonal parameter values for average plane and Solitario Canyon plane elements

Month	Sat	Set 1 KS (mm/hr)	Set 2 KS (mm/hr)
January–April	0.325	22.25	20.2
May–June	0.155	22.25	20.2
July–October	0.155	11.25	20.2
November	0.235	11.25	20.2
December	0.235	22.25	20.2

Table 6-3. Statistical summary for average plane runoff and Solitario Canyon channel infiltration

Parameter set	Mean annual runoff (mm/yr)	Number of runoff events	Number of runoff events => 0.1 mm	Number of events for 75 percent of runoff	Mean annual channel infiltration (mm/yr)	Number of events for 75 percent of infiltration
Set 1	1.51	155	77	24	0.57	35
Set 2	0.38	80	44	16	0.18	31

The peak runoff rates for these two storms for both sets of parameter values are plotted versus area for the Solitario Canyon watershed and four subwatersheds in figure 6-2a,b. Peak flows calculated from the maximum stage data (table 3-2, U.S. Department of Energy, 1988) are shown on the same plot but without connecting lines. The labels for the stage data points are from the source table. The USGS 100-yr regional flood frequency curve (Squires and Young, 1984) is also shown. The T=101 curve for Set 1 simulations exceeds the USGS 100-yr curve and the T=16.8 curve exceeds all of the peak rates calculated from the measured peak stages, suggesting that the peak runoff rates generated for this parameter set are probably greater than would be observed. The T=101 curve for Set 2 simulations lies below the 100-yr USGS curve. The T=16.8 curve is exceeded by 5 of the 6 peak rates calculated from the peak stage data, suggesting that the peak runoff rates generated by this parameter set are probably lower than would be observed. Because channel infiltration is closely related to runoff volume and peak flow rates, it appears the values of channel infiltration cited previously may bracket the true rates.

A rainfall hyetograph and runoff hydrographs for a midwatershed channel and the lowermost channel for the storm 11SEP5A are shown in figure 6-3. The peak discharge at the mouth of Solitario Canyon has a recurrence internal of about 10 yr. This figure illustrates the rather complicated rainfall intensity patterns that can be generated by the rainfall disaggregation technique and the decrease in the peak discharge per unit area with increasing watershed area.

6.3 COMPARISON OF RESULTS WITH THOSE OF OTHER STUDIES

There have been no other attempts to estimate channel infiltration in the Solitario Canyon watershed. Estimates, however, have been made for channel infiltration in nearby watersheds of similar size and elevation. Osterkamp et al. (1994) used a geomorphic/distributed parameter approach to estimate channel infiltration for tributaries of the Amargosa River. For the washes nearest in size to Solitario Canyon, Yucca Wash (21.9 km^2) and Drillhole Wash (39.9 km^2), which drain the east side of YM, they estimated average annual channel infiltration rates of 5.93 and 1.25 mm/yr respectively. Savard (1998) used streamflow measurements and estimates for the period 1983–1995, in conjunction with a linear model of groundwater recharge from streamflow losses to estimate groundwater recharge in Fortymile Wash, east of YM. For the combined reaches of Upper Jackass Flats and Lower Jackass Flats (150 km^2), he estimated an annual volume of recharge of 0.117 mm/yr for the main channel of Fortymile Wash. This neglects recharge from the tributary channels, so the total recharge would be greater.

The average depth of channel infiltration for this study (12–38 mm/yr) is larger than the 10-mm/yr recharge based on an estimation of percolation flux for nearby Pagany and Drillhole Washes (Kwicklis and Rousseau, 1996). This difference is expected because recharge should be less than channel infiltration, reflecting losses due to evaporation and transpiration by vegetation in and near the channels.

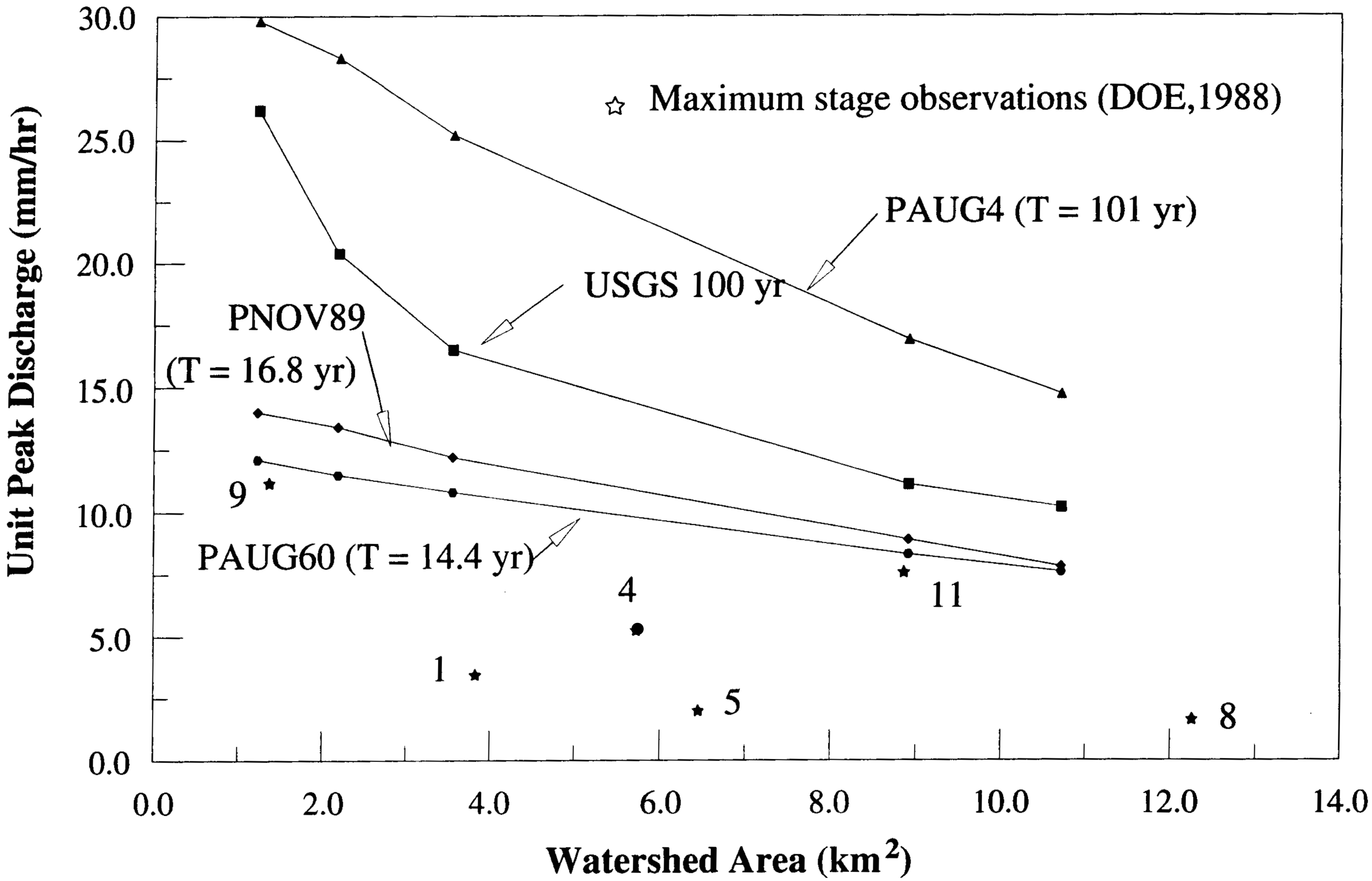


Figure 6-2a. Observed and simulated peak discharge rates versus watershed area for similar recurrence intervals; Set 1, seasonally varied KS

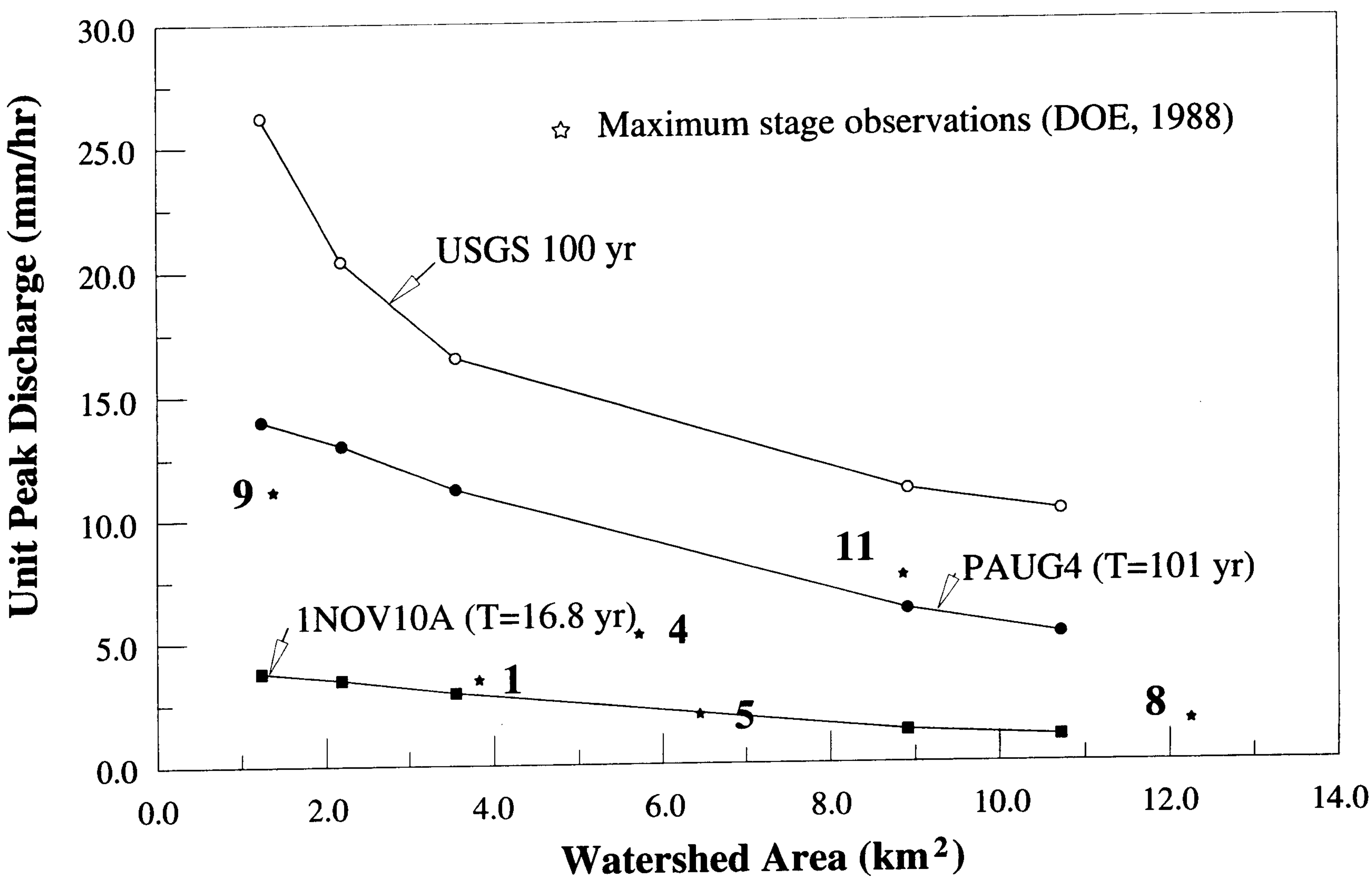


Figure 6-2b. Observed and simulated peak discharge rates versus watershed area for similar recurrence intervals; Set 2, KS = 20.2 mm/hr

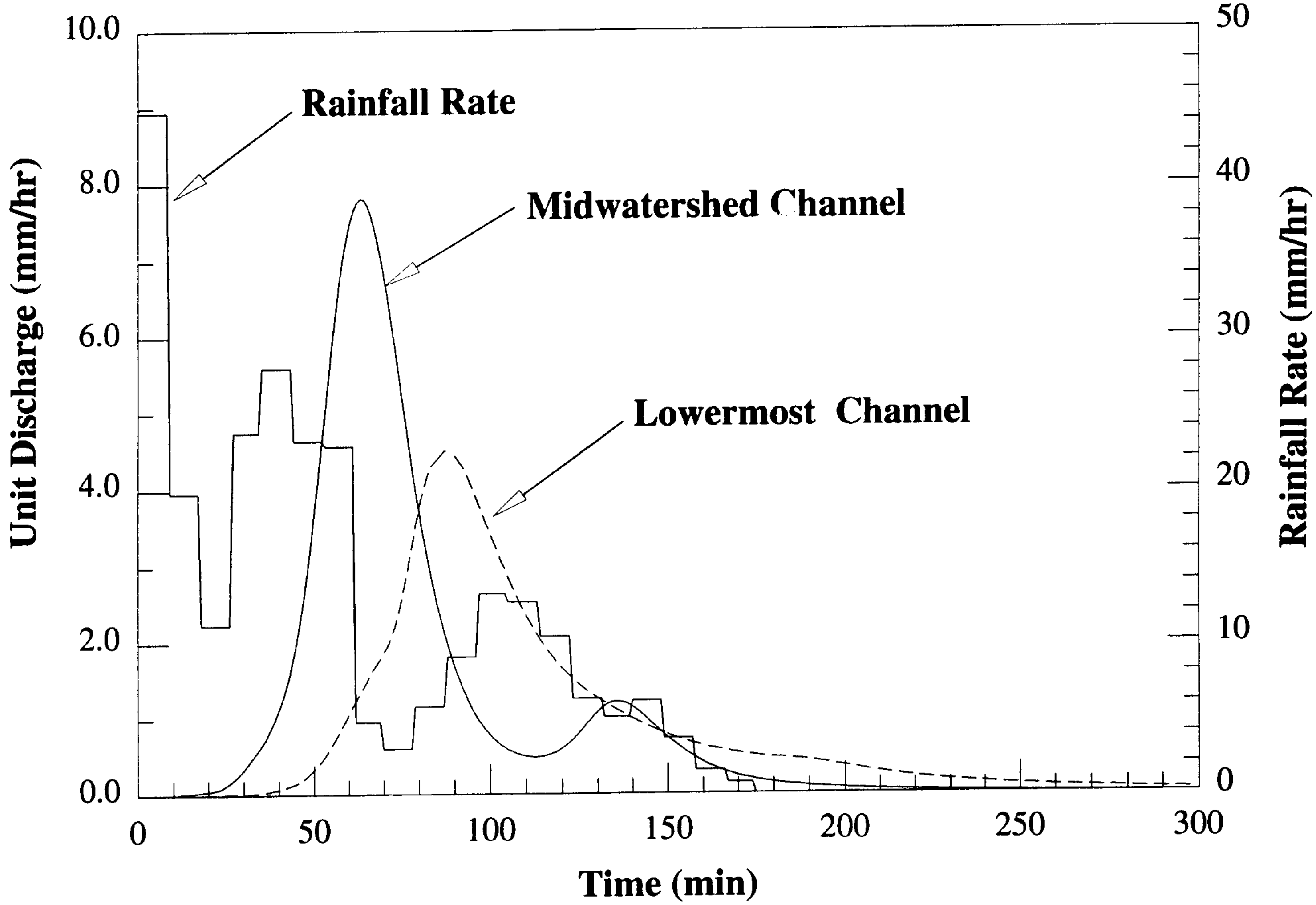


Figure 6-3. Rainfall hyetograph for storm 11SEPA and runoff hydrographs for the main channel of Solitario Canyon at midwatershed and at the outlet

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7 SENSITIVITY

7.1 SOURCES OF ERROR

There are many sources of uncertainty involved in these simulations including input error, model error, and parameter error.

7.2 INPUT ERROR

Input uncertainties include (i) distortions in the daily and seasonal patterns of daily rainfall for Solitario Canyon because of an inappropriate choice of stations, inaccurate fitting of the records for the two stations used in USCLIMATE.BAS for creating the parameter set, or both; (ii) errors due to the two-stage disaggregation process; (iii) errors due to the threshold level of 12.7 mm used to identify significant storms, and (iv) errors due to neglecting the spatial variability of rainfall.

Johnson et al. (1996) compared the statistical characteristics of precipitation simulated by USCLIMATE, observed precipitation at six locations, and found that USCLIMATE preserved the monthly and annual means well but underestimated the variances. It also underestimated the daily maximum rainfall. Because much of the runoff and channel infiltration is caused by a few large storms, underestimation of rainfall extremes may lead to underestimation of runoff.

The intensity-duration-frequency statistics of the simulated storms were compared with statistics from nearby stations in figure 5-1a,b. It appears that the simulated intensities may be too high, which may compensate for the probable underestimates of extreme daily rainfall.

Neglect of rainy days with less than 12.7 mm would have little effect on runoff estimates. Neglect of showers below this threshold could have an effect on runoff if the shower occurred shortly after another runoff producing shower. Given the small number of showers per day in this arid environment, however, the effect is probably negligible.

A high degree of spatial variability of rainfall is common during thunderstorms in arid regions. Based on the work of Osborn et al. (1993), it appears that neglecting the spatial variability of rainfall will lead to an overestimation of runoff.

7.3 MODEL ERRORS

Model errors are most certainly present, but difficult to evaluate. The KINEROS2 model has been thoroughly tested on semiarid watersheds where runoff is generated by the Hortonian mechanism and it performed well for catchments up to 6.3 km^2 (Goodrich, 1990). Saturation overland flow may occur on shallow soils within the watershed during prolonged wet spells in the winter (Flint et al., 1996). Although KINEROS2 can model this phenomenon by specifying two soil layers, sufficiently detailed field data on the locations and extent of shallow soils were not available, so this feature was not modeled. An analysis of the 7-day accumulated rainfall prior to each significant storm suggests that saturation overland flow is infrequent and may be relatively unimportant because the runoff rates (and the channel wetted perimeters) would be small. In the third 50-yr simulation, for example, the 7-day antecedent precipitation was greater than 25.4 mm 16 times, was greater than 30 mm 7 times and was greater than 40 mm on only 2 occasions.

The channel geometry of Solitario Canyon is dependent on the scale of the map used to identify plane and channel elements. The effect of two different contour intervals was examined by modeling an area east of the main channel in the lower portion of Solitario Canyon as shown in figure 2-1. On the Solitario Canyon map with a 20-m contour interval, only one lateral channel was detected, while six lateral channels were detected on the map with a 10-ft contour interval. The subwatershed was subdivided into 95 plane and channel elements, whereas the simpler representation has only 13 plane and channel elements.

The effect of the topographic detail of the subwatershed was evaluated for two intense summer storms from the second 50-yr simulation. The hydrograph from the upper watershed was injected into the uppermost channel of the subwatershed. The detailed representation resulted in a 5-percent increase in channel infiltration over the simple model. The areas of channel bottoms are 11,581 m^2 for the detailed and 10,684 m^2 for the simple representations, including the areas of the main channel. If the main channel areas are eliminated, the channel areas are 1,531 m^2 for detailed and 634 m^2 for simple representations. Obviously, the detailed model has a greater drainage density.

An analysis of the computer output files for the storm of PAUG4 revealed an interesting phenomenon. A different parameter set than shown in table 6-2 was used for this analysis. For the main channel elements of the detailed model, the total infiltration was 3,986 m^3, while for the simple model, it was 4,330 m^3. For the tributary channels, however, the infiltration was 819 m^3 for the detailed case and 219m^3 for the simple cases. Thus, there was 8.62 percent more infiltration in the main channel for the simple case but about 5 percent less overall. It appears there will be more total channel infiltration with the more detailed topographic representation, but <u>less</u> infiltration in the main channel reaches. This raises an interesting question: Is there a difference in the proportion of water infiltrated into a channel that may reach groundwater depending on the size of the channel? It is likely that streamside vegetation may have greater opportunity to withdraw water from the alluvium in the smaller channels. There may also be a greater opportunity for water infiltrated into smaller channels to flow into rock fractures.

7.4 PARAMETER ERRORS

A thorough sensitivity study of the KINEROS2 model was made for the entire Solitario Canyon watershed. Two storms were used: 11SEP5A (a 10-yr storm) and PAUG4 (a 100-yr storm). Parameter values were perturbed by +20 percent from the reference case. The total rainfall amounts and durations were also increased by 20 percent, modifying the intensities for each time increment. Ranked dimensionless sensitivity coefficients for channel infiltration are shown in tables 7-1 and 7-2.

The model sensitivity is highly dependent on the magnitude of the input with higher sensitivity coefficients for the smaller event, reflecting the nonlinearity of the rainfall-runoff process. It is no surprise that the model is most sensitive to the input rainfall intensity—this has been observed before for runoff volumes and peak rates. It is significant that the parameter sensitivity rankings also depend on the storm magnitude, with plane infiltration parameters more important for the smaller storm and channel infiltration parameters having a greater effect on channel infiltration for the 100-yr storm. Sensitivity coefficients were also calculated for runoff volume and peak rate. The sensitivity coefficients for channel infiltration were smaller than the coefficients for peak rates and volume.

Table 7-1. Ranked sensitivity coefficients for channel infiltration, 10-yr storm 11SEP5A

Parameter or Input	Sensitivity Coefficient
Rainfall depth	2.23
KS, plane	-1.10
Rain duration	-1.01
G, plane	-0.60
KS, channel	0.53
n, channel	0.47
CV, plane	0.35
KS, small channels	0.25
n, plane	-0.094
SAT, plane	0.094

Table 7-2. Ranked dimensionless sensitivity coefficients for channel infiltration, 100-yr storm PAUG4

Parameter or Input	Sensitivity Coefficient
Rainfall depth	1.06
KS, channel	0.47
n, channel	0.45
KS, plane	-0.24
KS, small channels	0.22
G, plane	-0.19
Rain duration	-0.19
RELIEF, plane	0.043
n, plane	-0.043
Channel width	0.043

It is important to note that the channel infiltration is relatively insensitive to the channel bottom width. This is a result of interaction between the channel width and the algorithm in KINEROS2 that calculates the effective infiltrating channel width as a function of depth (Eq. 2-2). The row KS, small channels refers to a parameter file where KS of all channels other than the main channel was reduced by 20 percent. The net result was a decrease in the total channel infiltration but an increase of infiltration into the main channel elements. This is the type of response that would be expected if there is some rejection of infiltration in the smaller channels due to shallow alluvium.

8 CONCLUSIONS AND RECOMMENDATIONS

This investigation has provided some useful insights into the problem of estimating infiltration due to surface runoff in the channels of the Solitario Canyon watershed. The following conclusions appear justified.

Simulation of daily rainfall and the procedure for disaggregating daily rainfall into showers and intensity patterns within the showers provides simulated storms with intensity-duration-frequency statistics that compare favorably with depth-duration-frequency curves prepared by French (1983) for nearby stations.

Based on a 100-yr simulation of daily and storm rainfall, the mean annual infiltration from surface runoff in the channels of the Solitario Canyon watershed is estimated to be between 0.18 and 0.57 mm/yr expressed as depth over the entire watershed and between 12 mm and 38 mm over the channel area. Both the surface runoff volumes and the channel infiltration volumes are smaller than the estimates of Osterkamp et al. (1994) for nearby watersheds. Based on comparisons of simulated peak rates of runoff with estimates from maximum stage gages in nearby watersheds, the runoff estimates appear reasonable. By neglecting to model shallow soils, runoff and channel infiltration from winter storms are probably underestimated.

No attempt was made to estimate the portion of channel infiltration that becomes groundwater recharge, so the greater of the infiltration estimates should be considered as an upper bound.

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